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Our galaxy's collision with Andromeda

The Milky Way's destruction will come in a clash with the Andromeda Galaxy.
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Five billion years from today, the night sky will blaze with stars and gas as the Milky Way merges with the Andromeda Galaxy.

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5 billion years A.D.

Our galaxy's date with destruction

The Milky Way is on a collision course with its neighbor, the Andromeda Galaxy. What will the night sky look like after the crash? /// BY ABRAHAM LOEB AND T.J. COX

Our galaxy, the Milky Way, and its nearest large neighbor, the Andromeda Galaxy (M31), are on a collision course. Billions of years from now, the merger will transform the structure of both galaxies and create a new arrangement of stars we have dubbed Milkomeda ("milk-AHM-mee-da"). The merger will radically transform the night sky. But into what?

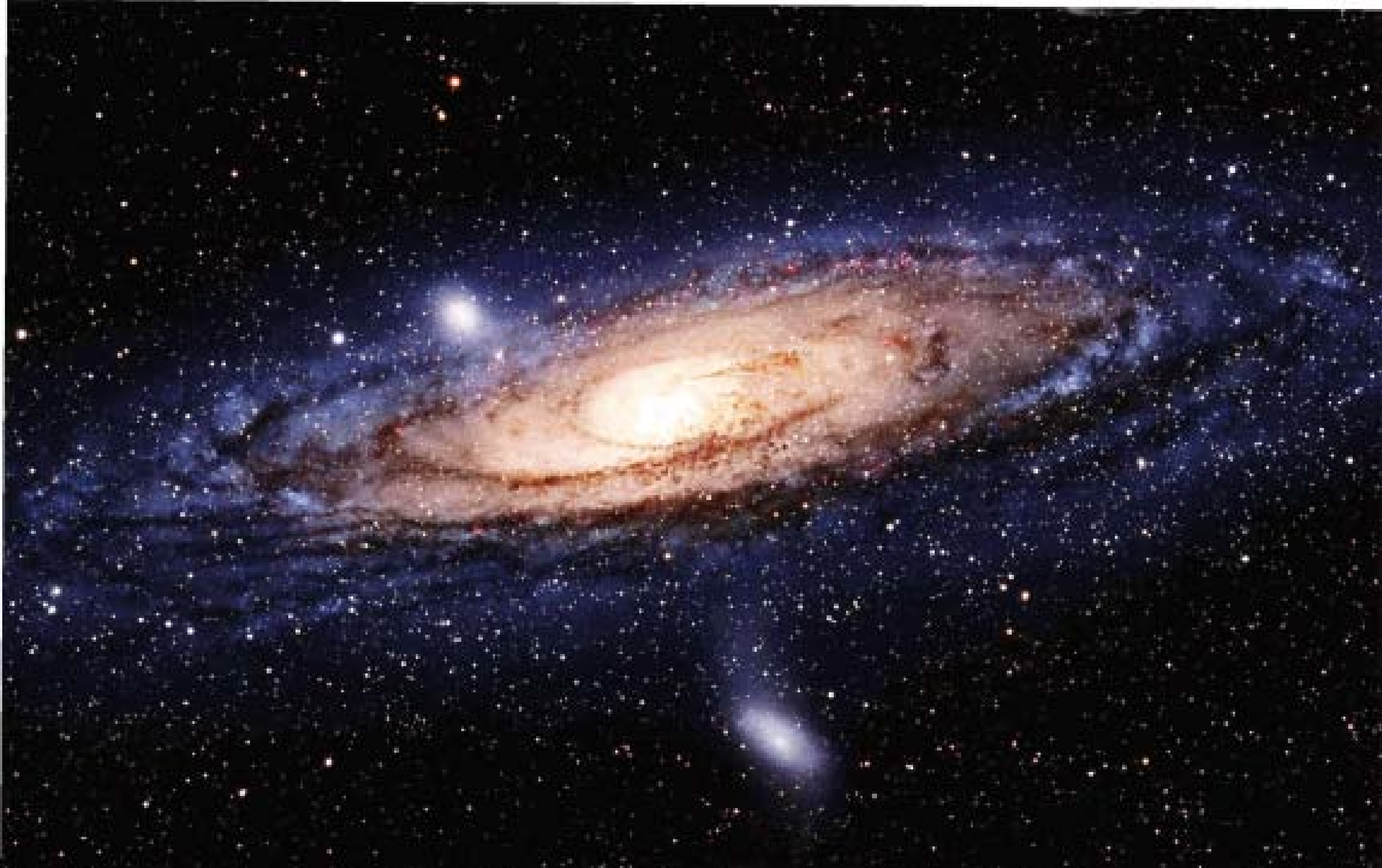
Currently, the Milky Way's thin disk of stars and gas appears as a nebulous strip arching across the sky. As Andromeda grazes the Milky Way, a second strip of stars will join the one that presently graces the night sky in summer. After the final merger, the stars will no longer be confined to two narrow lanes, but instead scatter across the entire sky.

In our research, we have explored the Milky Way's fate by simulating Milkomeda's birth in a supercomputer. The simulations are at a sufficient level of detail (resolution) to learn a lot about the coming merger and how it will change our perspective on the universe. Although we won't be here to witness the event — nor to take responsibility for whether our forecast proves accurate — this is the first research in our careers that has a chance of being cited 5 billion years from now.

The Local Group

The night sky's vastness might suggest the Milky Way resides in a relatively remote part of the universe. However, astronomers know the Milky Way to be the second-largest in the Local Group of galaxies, compared to Andromeda, which is the largest member. It contains somewhat more mass than the Milky Way, lies nearly 2.5 million light-years away,

BILLIONS OF YEARS FROM NOW, the night sky will glow with stars, dust, and gas from two galaxies: the Milky Way, in which we live, and the encroaching Andromeda Galaxy (M31). LYNETTE COOK FOR *ASTRONOMY*



THE ANDROMEDA GALAXY (M31) is a typical spiral of stars, dust, and gas. Spiral galaxies dominate the night sky in the local universe. Fourteen satellite galaxies accompany Andromeda, including the two visible in this image: M32 (above Andromeda) and NGC 205 (below). Andromeda is the largest in the Local Group of galaxies. TONY AND DAPHNE HALLAS

and is visible in the northern sky with the naked eye. The remaining members of the Local Group — several dozen — are a bevy of much smaller satellite galaxies.

A galaxy group comprises two or more relatively close, massive galaxies. The compactness of galaxies that form groups suggests that they are gravitationally bound and dynamically coupled to each other. This simply means the galaxies attract each other gravitationally, so a change in one affects the fate of the other.

Evidence of the dynamic connection between the Milky Way and Andromeda comes from their relative motions. The galaxies are barreling toward each other at nearly 270,000 mph (190,000 kilometers per hour). We know this because the spectral lines of Andromeda's light appear to be blueshifted — displaced toward the blue end of the spectrum — by the Doppler effect. In contrast, most galaxies in the universe are flying away from the Milky Way.

Timing is everything

Nearly 50 years ago, Franz Kahn and Lodewijk Woltjer pioneered the "timing argument." This hypothesis held that the Milky Way and Andromeda formed close to each other, during the dense, early stages of the universe.

Subsequently, the general expansion of the universe pulled the two galactic neighbors apart. Later, the Milky Way and Andromeda reversed their outward trajectories owing to mutual gravitational attraction. Since then, they have completed nearly a full orbit around each other.

The timing argument, combined with estimates of the galaxies' relative velocities and other factors, indicates the Local Group's total mass is about 3 trillion times the Sun's mass. It also suggests the Milky Way and Andromeda will make a close pass in about 4 billion years.

Kahn and Woltjer inspired a generation of studies that further constrained the mass of the Local Group and revealed important characteristics of Andromeda's orbit, such as its total energy of motion.

But the timing argument does not have the ability to follow the complex dynamics that accompany the merger of extended galaxies. Therefore, it cannot predict the future arrangement of the Local Group. For processes as complex as galaxy mergers, astronomers need more powerful tools.

Simulating the Local Group

Numerical simulations are indispensable for understanding processes too complex to solve with pen and paper. In galactic mergers, for example, simple gravity shapes the merged galaxy. But the sheer number of atoms interacting over time makes it difficult or impossible to simulate the merger without massive computer power.

To simulate the evolution of the Local Group, first we create a mathematical model describing its present state. This is straightforward for the Milky Way and Andromeda. Several decades of observations enable us to

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estimate the quantity gas, stars, and other matter involved. We can determine a plausible mass estimate for the Milky Way and Andromeda to well beyond the visible inner portion of each galaxy.

However, the combined mass of the Milky Way and Andromeda is still less than nearly every number the timing argument yields. This implies there is additional mass in the Local Group.

The missing mass turns out to be the diffuse "intergalactic medium" of atoms, gas, and dust between the galaxies. Galaxies are simply the visible peaks of massive icebergs of matter. Much of the mass is not readily apparent, just as most of an iceberg's bulk lies underneath the water's surface.

FROM EARTH, we see the Milky Way from an insider's perspective. Depending on the time of year, an Earth-bound observer can see 3 or 4 different arms of the spiral. JOHN CHUMACK

When galaxies collide

Full-scale simulations typically require 2 weeks of number crunching. This task requires the power of the equivalent of 16 fully loaded desktop computers.

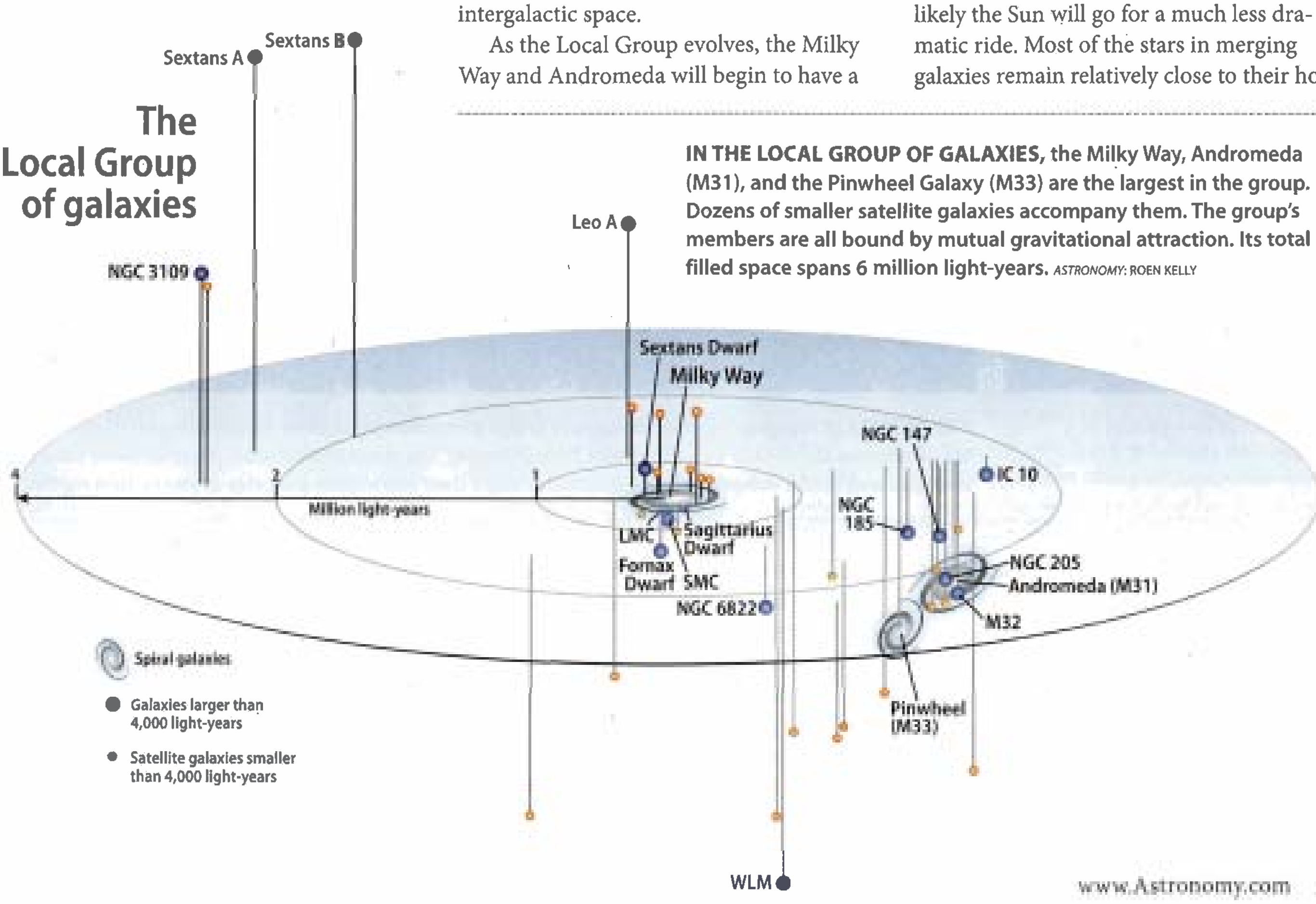
Since the early days of astronomy, merging galaxies have remained curiosities owing to their complex and irregular shapes. But astronomers now appreciate that mergers significantly drive galaxy evolution. Galaxy mergers touch off bursts of star formation, give birth to bright galactic nucleii (quasars), and transform pinwheel-shaped spiral galaxies into smooth spheroidal or elliptical galaxies.

One of the distinguishing characteristics of galaxy interactions is the appearance of long streams of stars and gas that stretch from one or both of the participant galaxies. We commonly call these features tidal tails. They result from the powerful gravitational forces at work between merging galaxies. As the tails form, they rip stars and gas from the host galaxy and hurl it into intergalactic space.

As the Local Group evolves, the Milky Way and Andromeda will begin to have a dynamic impact upon each other owing to their mutual gravitation. As a result, it's possible the Sun — and Earth and the other planets — will be dragged into a tidal tail. During this period, an observer would have one of the most unique vantage points imaginable. Torn shreds of the Milky Way will fill a large fraction of the night sky as our galaxy experiences its gravitational dance with Andromeda.

Because only a small fraction of a galaxy's mass ends up in tidal tails, it is more likely the Sun will go for a much less dramatic ride. Most of the stars in merging galaxies remain relatively close to their host

The Local Group of galaxies



IN THE LOCAL GROUP OF GALAXIES, the Milky Way, Andromeda (M31), and the Pinwheel Galaxy (M33) are the largest in the group. Dozens of smaller satellite galaxies accompany them. The group's members are all bound by mutual gravitational attraction. Its total filled space spans 6 million light-years. *ASTRONOMY*: ROEN KELLY

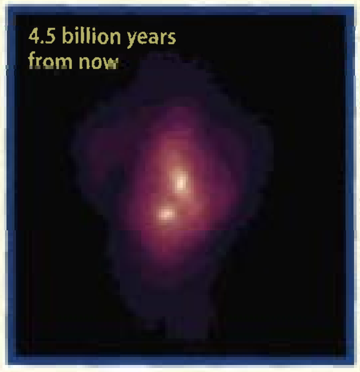
GALAXY MERGERS IN CYBERSPACE

Astronomers don't simulate galaxy mergers just to create pretty pictures. The simulations are serious and time-consuming scientific experiments. Simulations enable astronomers to test new ideas about the merger process and the role of mergers in the evolution of galaxies and the universe.

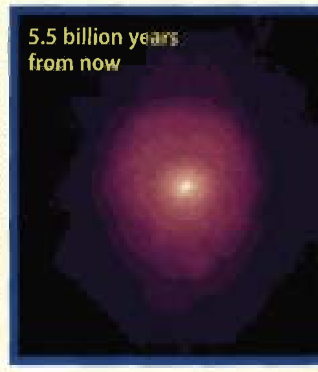
The images below, sampled from a merger simulation by Harvard astronomers T. J. Cox and Avi Loeb, depict the merger of the Milky Way and Andromeda galaxies. These frames highlight important milestones and events in the merger process. UNLESS OTHERWISE NOTED, MERGER IMAGES BY T.J. COX (CfA)

2 BILLION YEARS from the present, the galaxies swing around each other in a close pass. Mutual attraction draws tenuous tidal tails of stars and gas. Tidal tails are hallmarks of mergers in the real universe (see image below).

IN 2.5 BILLION YEARS, the galaxies are still moving apart. A ghostly bridge of gas and stars still connects them. Stars in the bridge, perhaps some with planets, could end up literally lost in space as the galaxy bridge dissipates.

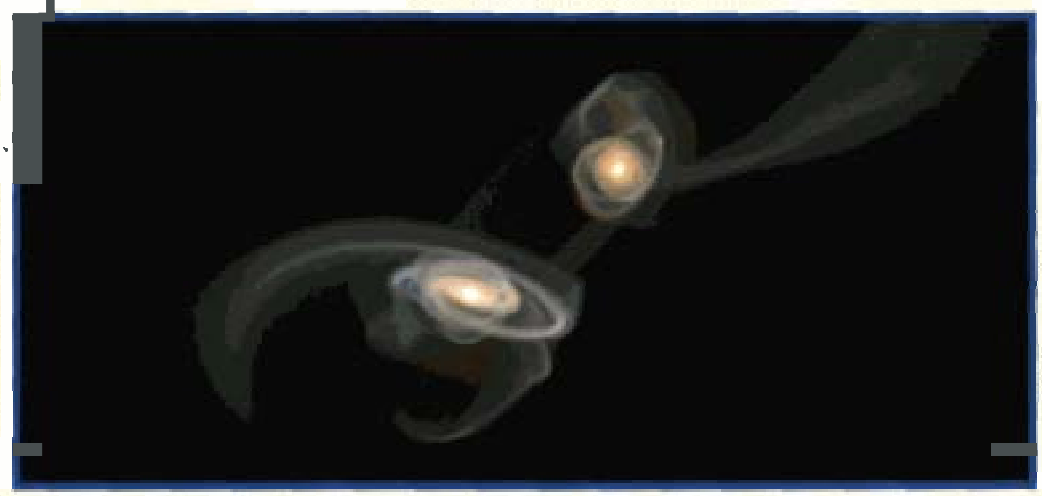


IN 4.5 BILLION YEARS, the galaxies loop around another time and then finally coalesce into a single mass. Their dense cores, each harboring a black hole, gradually combine into a single nucleus. The merging galaxies experience a brief pulse of star formation as the black holes merge.



IN 5.5 BILLION YEARS, Milkomeda is born. Tidal swirls, tails, and eddies left over from the violent merger slowly relax and dissipate. Individual stars spread out, forming a more homogenous elliptical galaxy similar to M32 (right), a satellite of today's Andromeda Galaxy.

NGC 2207 (lower galaxy) as it merges with smaller IC 2163.
NASA/ESA/HUBBLE HERITAGE TEAM (STScI)



JOHN DUBINSKI (WWW.GALAXYDYNAMICS.ORG)

THE BEAUTY of merging galaxies stands out in this simulation of another possible model of the Milky Way-Andromeda collision by astronomer John Dubinski. The simulation reveals more detailed structure than Cox and Loeb's images because it includes more than 300 million particles of interacting matter.

galaxies. The chance of the Sun being banished to the tidal-tail boondocks is relatively small, based on our simulations.

Change of fortune

The Sun's peaceful orbit around the center of the Milky Way — which it has traversed nearly 20 times since its birth — will forever change. Its new path will be far more chaotic owing to the rapid fluctuations in gravity induced by the merger. What would this mean for Earth and its residents?

Our research suggests the Milky Way and Andromeda will begin to interact strongly 2 billion years from now, and then complete the merger in about 5 billion years. The latter date is especially notable because it coincides with the Sun's remaining life span. Currently, our Sun is about halfway through its lifetime and eventually will begin to expand. As it does so, it will consume all its available hydrogen and evolve toward a red-giant phase within 5 billion years. In short, the Sun will be in its death throes on Milkomeda's birthday.

The Sun's red-giant stage will make life on Earth rather uncomfortable. Indeed, it

THE MERGER OF SPIRALS often produces a single, new sphere-shaped type of galaxy called an elliptical. The elliptical galaxy above, M32, is one of the 14 known satellite galaxies of Andromeda. Most galaxies in the Local Group are small satellites. WOLFGANG PROMPER

will spell the end of life as we know it. However, it does not preclude the possibility for colonization of habitable planets around nearby stars. Thus, it is possible future astronomers will be able to witness some, if not all, of the Local Group evolution we have simulated.

Although the Milky Way and Andromeda will merge, stars within the two galaxies, such as our Sun, will not physically collide. The reason is the extremely large distances between individual stars in galaxies. For example, if the Sun were the size of a ping-pong ball, the nearest star (Proxima Centauri) would be another ping-pong ball nearly 1,000 miles (1,600 km) away.

Our final resting place

The Sun's orbit will follow a chaotic path until the merger concludes. At that point, the system will relax and expand. And the Sun will reside inside a new galaxy: Milkomeda. It will look very different from either the Milky Way or Andromeda.

The Milky Way and Andromeda are spiral galaxies, with most stars concentrated into a disk and moving in nearly circular orbits around the galactic center. In contrast, Milkomeda will be nearly spherical in shape and much smoother in appearance than any spiral galaxy. Stars within Milkomeda will follow more complex orbits. The stars will spend brief periods near the dense galactic center, but orbit much farther away most of the time.

Milkomeda's spheroidal shape is not unusual, as it characterizes a major class of objects called elliptical galaxies. Such galaxies typically host relatively old stars. Presumably, many of these galaxies in the present-day universe formed by mergers between galactic disks, in which the stars had formed at earlier cosmic times.

The Sun's likely fate will be to spend much of its time in the galactic outskirts. The merger will redistribute the orbital momentum (energy) of the Milky Way and Andromeda among individual stars in Milkomeda. The stars will end up with more momentum after the merger, and thus will encircle Milkomeda's center at a larger average distance.

The Local Group's far future fate

Because of the universe's accelerating expansion, Milkomeda will not merely be our final resting place. A hundred billion years later, Milkomeda also will represent our entire visible universe.

In the next tens of billions of years, the accelerating expansion of space itself will pull all distant galaxies farther and farther away from us. Once the recession rate of any distant galaxy exceeds the speed of light relative to us, its light will be unable to traverse the inflating gap.

At that point, we will no longer be able to see those galaxies. They will gradually wink out of reach of the most powerful telescopes. No longer will astronomers be able to gaze into the sky and study distant galaxies in order to learn about our own.

However, the prelude to this final gloomy fate would be full of fun. Over the next 5 billion years, astronomers will witness the stellar fireworks in one of the greatest shows of all time: the transformation of the Milky Way and the Andromeda Galaxy into Milkomeda. So sit back and wait for the show to begin. ■

WEB EXTRA Watch animation of the Milky Way and Andromeda galaxies merging at www.Astronomy.com/toc.